

Searching for Z' Gauge Boson in an Anomaly-Free $U(1)'$ Gauge Family Model

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Abstract

We study a simple ultraviolet(UV) complete and anomaly free Z' model based on a $U(1)'$ gauge family symmetry without introducing extra fermions beyond the standard model. The $U(1)'$ group is diagonal in the three family space in which the $U(1)'$ charges of the first and second families are the same but different from those of the third family. After spontaneous symmetry breaking and rotating to the mass eigenstates of quarks and leptons, there exist in general both flavor-conserving and flavor-changing couplings. In flavor conserving case, we use the latest dijet and dilepton search at the LHC to constrain the mass and gauge couplings of Z' . Also we show that in the flavor-changing and left-right asymmetry case, the t-channel Z' process can only contribute to part of the forward-backward asymmetry in the top quark pair production observed at the Tevatron by taking into account the constraint from same sign top production at the LHC.

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I. INTRODUCTION

Theoretically, one of the simplest and best motivated extensions of the standard model(SM) is the introduction of an additional $U(1)'$ gauge symmetry with the associated gauge boson Z' [1]. Such an $U(1)'$ gauge symmetry often appears in grand unified theories, such as $SO(10)$ or E_6 theories. Phenomenologically, as the extra $U(1)'$ gauge symmetry can result in new interactions between the new gauge boson and the SM particles, it can lead to some interesting phenomena or explanations for possible experimental results away from the SM predictions [2].

In gauge theories, the cancelation of anomaly is tightly connected with renormalizability. In the grand unified theories [3] with a large group, such cancelation for $U(1)'$ subgroup can be satisfied and new particles if any fill in, automatically. For phenomenological Z' models, with an additional gauge group introduced, usually the anomaly is canceled with introducing by hand new chiral fermions. Since no new fundamental fermion is observed yet, these new particles have to be heavy and usually difficult to be probed.

From an economical perspective, it is interesting to ask what an $U(1)'$ model looks like if introducing no new chiral fermion. For family universal $U(1)'$ models, unlike family non-universal ones discussed in [4–12], there is no problem like flavor-changing neutral currents(FCNC) effects. However, for such models, there is little room left if no new particles are added as we shall show later. Then we shall not restrict the discussion within family non-universal models and but taking FCNC suppression as an requirement or constraint.

In the present paper, based on the structure of non-linear equations from anomaly cancelation that constrain the $U(1)'$ charges of SM fermions, we shall show a simple UV complete and anomaly free Z' model without introducing any exotic fermions beyond the SM. In this model, the $U(1)'$ charges of the first and second families are the same but different from the third family. A specific feature of this model is that the cancelation of anomalies is satisfied separately in lepton and quark sectors. In general, there can exist both flavor conserving and flavor changing interactions of Z' gauge boson with quarks and leptons after spontaneous symmetry breaking and rotating to the mass eigenstates of quarks and leptons.

Our paper is organized as follows. In Sec.II, we give a brief summary for the anomaly-cancelation conditions of an extra $U(1)'$ gauge symmetry with the SM particles and the arguments that lead to our model. In Sec. III, we provide a detailed description on our Z' model for the fermion and higgs sectors. In Sec. IV, for flavor-conserving case we use the latest experiments direct search to constrain the parameters of the model and discuss for flavor-changing case an observable effect, forward-backward asymmetry of top pair production. Our conclusions are given in the last section.

II. $U(1)'$ ANOMALY CANCELATION

The requirement of vanishing of anomalies is usually used as a guide in building realistic renormalizable theories and many models are then accompanied with new chiral fermions to satisfy the requirement. These models may or may not have a unification origin, but in common they include many particles which is usually too heavy to be detected. For realistic reason, we shall restrict ourselves here to study an anomaly free $U(1)'$ model without introducing any new fermions, and we find a family non-universal model based on simple and reasonable assumptions.

When introducing an additional $U(1)'$ gauge symmetry to the SM, we can assign the $U(1)'$ charges $z_{\#}$ to all the SM particles as shown in Table I. In the following discussions,

like mentioned above, we shall not introduce any exotic fermions. The weak doublets and

	SU(3) _c	SU(2) _L	U(1) _Y	U(1)'
Q_L^i	3	2	+1/3	z_{Q^i}
u_R^{i*}	$\bar{3}$	1	-4/3	$z_{u_i^*}$
d_R^{i*}	$\bar{3}$	1	+2/3	$z_{d_i^*}$
L^i	1	2	-1	z_{L^i}
$e_{R,i}^*$	1	1	+2	$z_{e_i^*}$
$\nu_{R,i}^*$	1	1	0	$z_{\nu_i^*}$

TABLE I:

singlets are denoted as follows, $\psi = u, d, e, \nu$,

$$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}, \quad L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}, \quad \psi_{L,R}^i = P_{L,R} \psi^i,$$

with $P_L = (1 - \gamma_5)/2$, $P_R = (1 + \gamma_5)/2$.

The anomaly is proportional to the completely symmetric constant factor,

$$D_{\alpha\beta\gamma} \equiv \text{tr} [\{T_\alpha, T_\beta\} T_\gamma]$$

T_α is the representation of the gauge algebra on the set of all left-handed fermion and anti-fermion fields, and “tr” stands for summing over those fermion and anti-fermion species. The anomaly free conditions for the theory are given by

$$\begin{aligned}
0 &= \sum_{i=1}^3 (2z_{Q_i} + z_{u_i^*} + z_{d_i^*}), \quad [SU(3)^2 U(1)'], \\
0 &= \sum_{i=1}^3 (3z_{Q_i} + z_{L_i}), \quad [SU(2)^2 U(1)'], \\
0 &= \sum_{i=1}^3 \left(\frac{1}{6} z_{Q_i} + \frac{4}{3} z_{u_i^*} + \frac{1}{3} z_{d_i^*} + \frac{1}{2} z_{L_i} + z_{e_i^*} \right), \quad [U(1)_Y^2 U(1)'], \\
0 &= \sum_{i=1}^3 (6z_{Q_i} + 3z_{u_i^*} + 3z_{d_i^*} + 2z_{L_i} + z_{e_i^*} + z_{\nu_i^*}), \quad [\text{global } U(1)'], \\
0 &= \sum_{i=1}^3 (z_{Q_i}^2 - 2z_{u_i^*}^2 + z_{d_i^*}^2 - z_{L_i}^2 + z_{e_i^*}^2), \quad [U(1)'^2 U(1)_Y], \\
0 &= \sum_{i=1}^3 (6z_{Q_i}^3 + 3z_{u_i^*}^3 + 3z_{d_i^*}^3 + 2z_{L_i}^3 + z_{e_i^*}^3 + z_{\nu_i^*}^3), \quad [U(1)'^3]. \tag{1}
\end{aligned}$$

Here i is the family index.

These equations are non-linear and have too many free parameters. To solve these equations, some assumptions are usually made, for instance, family universal charges assignment. In family universal models, anomaly cancelation is separately satisfied in each family. However, family universality is not a necessary condition, and more generally, there can exist family non-universal models as we show in the follows.

From the first four linear equations, we get three equations for the quark sector

$$\begin{aligned}
\sum_{i=1}^3 z_{d_i^*} &= \sum_{i=1}^3 \left(\frac{4}{3} z_{L_i} + z_{e_i^*} \right), \\
\sum_{i=1}^3 z_{u_i^*} &= - \sum_{i=1}^3 \left(\frac{2}{3} z_{L_i} + z_{e_i^*} \right), \\
\sum_{i=1}^3 z_{Q_i} &= - \frac{1}{3} \sum_{i=1}^3 z_{L_i},
\end{aligned} \tag{2}$$

and one for the neutrino sector

$$\sum_{i=1}^3 z_{\nu_i^*} = - \sum_{i=1}^3 (2z_{L_i} + z_{e_i^*}).$$

Right-handed neutrinos are introduced here since we now know neutrinos have masses but whether they are Dirac or Majorana particles is still unknown. Here and after, we will focus on the quark sector and not discuss neutrinos any further.

III. REALISTIC Z' BOSON MODEL

The LEP II and hadron colliders have put stringent limits on the Z' boson of popular models [1], including its mass and couplings to leptons as well as the mixing angle with Z , by using mostly the lepton decay channel of Z' boson. To fit the experimental results and escape the limits, an usual assumption made in the literature is that the Z' couplings with the leptons are much smaller than those with quarks, namely the $U(1)'$ charges of leptons are much smaller than those of quarks. Those models are called leptophobic Z' models. Actually, leptophobic theory is not so strange as we do have a similar structure in standard model, i.e., $SU(3)_c$ QCD of strong interaction.

A. Anomaly cancelling separately in quark and lepton sectors

In our present considerations, we will not impose leptophobic structure as a constraint in our model, but treat the $U(1)'$ charges of quarks and leptons to be independent with the only constraint from the anomaly cancelation. From eq. (2), the $U(1)'$ charges of leptons and quarks should naturally be at the same order. If there is a hierarchy in charges of lepton and quark sectors, there should be, among their charges, some extra or hidden relations which are beyond the scope of our discussions in this paper.

It is interesting to notice that in the linear equations given in eq. (2), when both sides of the equations are zero, the cancelation of $U(1)'$ anomalies may be satisfied separately in lepton and quark sectors among three families, based on their similar structures in the last two non-linear equations of eqs. (1). In that case, the charges of quarks are unrelated to

those of leptons, and then the equations for quarks read

$$\begin{aligned}
0 &= \sum_{i=1}^3 z_{Q_i}, 0 = \sum_{i=1}^3 z_{u_i^*}, 0 = \sum_{i=1}^3 z_{d_i^*}, \\
0 &= \sum_{i=1}^3 (z_{Q_i}^2 - 2z_{u_i^*}^2 + z_{d_i^*}^2), \\
0 &= \sum_{i=1}^3 (2z_{Q_i}^3 + z_{u_i^*}^3 + z_{d_i^*}^3).
\end{aligned} \tag{3}$$

and similar equations for leptons,

$$\begin{aligned}
0 &= \sum_{i=1}^3 z_{L_i}, 0 = \sum_{i=1}^3 z_{e_i^*}, 0 = \sum_{i=1}^3 z_{\nu_i^*}, \\
0 &= \sum_{i=1}^3 (-z_{L_i}^2 + z_{e_i^*}^2), \\
0 &= \sum_{i=1}^3 (2z_{L_i}^3 + z_{e_i^*}^3 + z_{\nu_i^*}^3).
\end{aligned}$$

Note that the sum over family indices, and that if anomaly cancelation occurs in each family, then all charges are zero, a trivial assignment.

B. Family Universality for the First and Second Families

Family non-universality generally leads to flavor mixing among fermions in their interactions with Z' boson in the mass eigenstates. In order to suppress the FCNC effects to fit the experimental results, especially the FCNC in the first two families are strongly constrained from the kaon meson system, thus we consider $U(1)'$ charges of the first and second families to be the same,

$$z_{Q_1} = z_{Q_2}, z_{u_1^*} = z_{u_2^*}, z_{d_1^*} = z_{d_2^*}.$$

With this assumption, the last two equations given in Eq. (3) can be written as

$$\begin{aligned}
\sum_{i=1}^3 (z_{Q_i}^2 - 2z_{u_i^*}^2 + z_{d_i^*}^2) &= 0 \Rightarrow z_{Q_1}^2 - 2z_{u_1^*}^2 + z_{d_1^*}^2 = 0, \\
\sum_{i=1}^3 (2z_{Q_i}^3 + z_{u_i^*}^3 + z_{d_i^*}^3) &= 0 \Rightarrow 2z_{Q_1}^3 + z_{u_1^*}^3 + z_{d_1^*}^3 = 0.
\end{aligned}$$

The above equations have a very simple solution

$$z_{u_1^*} = z_{d_1^*} = -z_{Q_1} \equiv -z.$$

Although this is not the only solution, while other five solutions are complex, irrational and complicated. We shall restrict ourselves to the above simple solution in our present consideration. We can rescale the coupling g'_1 so that $z = 1$ for later convenience.

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q_L^i	3	2	+1/3	(+1, +1, -2)
u_R^{i*}	$\bar{3}$	1	-4/3	(-1, -1, +2)
d_R^{i*}	$\bar{3}$	1	+2/3	(-1, -1, +2)

TABLE II: $U(1)'$ charges of quarks.

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
L^i	1	2	-1	$\mu(+1, +1, -2)$
e_R^{i*}	1	1	+2	$\mu(-1, -1, +2)$
ν_R^{i*}	1	1	0	$\mu(-1, -1, +2)$

TABLE III: $U(1)'$ charges of leptons.

For completeness, we also list the $U(1)'$ charges of the leptons. It is straightforward to check that the following assignment of the $U(1)'$ charges can satisfy the above equations, up to a constant μ relative to the quark sector. Here we will leave μ as an arbitrary constant. When $\mu \ll 1$, it becomes a leptophobic model. And $\mu \approx 1$ indicates that the $U(1)'$ charges of leptons and quarks are at the same order.

An important feature in this model is that the $U(1)'$ charges of the third family are as twice large as those of the first and second families. This feature reduces the branching ratio of $Z' \rightarrow l^- l^+$ ($l = e, \mu$) in dilepton search, and then the constraints may also be relaxed correspondingly. In the later discussion of experiment constraint, we will consider the limits from both the dijet and dilepton search.

C. Yukawa and Higgs sectors

Based on the $U(1)'$ charges of fermions, the SM Higgs doublet H_1 with zero $U(1)'$ charge can cause the spontaneous symmetry breaking to generate the masses of all the SM particles. The Yukawa interactions are

$$\begin{aligned}
\mathcal{L}_{H_1} = & \sum_{i,j=1}^2 f_{ij}^u \bar{Q}_{L,i} \tilde{H}_1 u_{R,j} + f_{33}^u \bar{Q}_{L,3} \tilde{H}_1 u_{R,3} \\
& + \sum_{i,j=1}^2 f_{ij}^d \bar{Q}_{L,i} H_1 d_{R,j} + f_{33}^d \bar{Q}_{L,3} H_1 d_{R,3} + h.c
\end{aligned} \tag{4}$$

The resulting two mass matrices have the following forms

$$\mathcal{M}_{u,d}^{H_1} \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}.$$

which shows that when the Yukawa term eq.(4) is the only interaction, it cannot obtain the realistic cabbibo-Kobayashi-Maskawa(CKM) matrix for quark mixing and CP violation. Thus we need to introduce two more Higgs doublets with non-zero $U(1)'$ charges. Specifically taking H_2 with $U(1)'$ charge -3 and H_3 with $+3$, we have the additional Yukawa interactions

for H_2 and H_3 ,

$$\begin{aligned}
\mathcal{L}_{H_{23}} = & f_{13}^u \bar{Q}_{L,1} \tilde{H}_2 u_{R,3} + f_{23}^u \bar{Q}_{L,2} \tilde{H}_2 u_{R,3} \\
& + f_{31}^u \bar{Q}_{L,3} \tilde{H}_3 u_{R,1} + f_{32}^u \bar{Q}_{L,3} \tilde{H}_3 u_{R,2} \\
& + f_{13}^d \bar{Q}_{L,1} H_3 d_{R,3} + f_{23}^d \bar{Q}_{L,2} H_3 d_{R,3} \\
& + f_{31}^d \bar{Q}_{L,3} H_2 d_{R,1} + f_{32}^d \bar{Q}_{L,3} H_2 d_{R,2} + h.c.
\end{aligned} \tag{5}$$

These Yukawa interactions will contribute to the mass matrices with

$$\mathcal{M}_{u,d}^{H_{23}} \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & 0 & \times \\ \times & \times & 0 \end{pmatrix}.$$

Similarly, one can write down the Yukawa interactions in the lepton section. Note that for $\mu \neq \pm 1$, two extra Higgs doublets have to be introduced.

When H_2 and H_3 get vacuum expectation values (VEVs), the $U(1)'$ gauge symmetry will also be broken as they carry nonzero $U(1)'$ charges. If the $U(1)'$ gauge coupling is at the same order as the electroweak coupling, the mass of Z' boson is then at the same order as the electroweak scale, which is highly constrained. To get a heavy Z' boson, we need to introduce a singlet scalar S with $U(1)'$ charge. With three Higgs doublets and their $U(1)'$ charges as well as a singlet scalar (its $U(1)$ charge z_s is unspecified), the most general gauge invariant Higgs potential is given by

$$\begin{aligned}
V_H = & -m_1^2 |H_1|^2 - m_2^2 |H_2|^2 - m_3^2 |H_3|^2 - m_S^2 |S|^2 \\
& + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_3|^4 + \lambda_S |S|^4 \\
& + \lambda_4 |H_1|^2 |H_2|^2 + \lambda_5 |H_1|^2 |H_3|^2 + \lambda_6 |H_2|^2 |H_3|^2 \\
& + \lambda_7 (H_1^\dagger H_2) (H_2^\dagger H_1) + \lambda_8 (H_1^\dagger H_3) (H_3^\dagger H_1) + \lambda_9 (H_2^\dagger H_3) (H_3^\dagger H_2) \\
& + [\lambda_{1s} |H_1|^2 + \lambda_{2s} |H_2|^2 + \lambda_{3s} |H_3|^2] |S|^2 \\
& + \left(\lambda_{10} H_1^\dagger H_2 H_1^\dagger H_3 + h.c \right)
\end{aligned} \tag{6}$$

where all parameters m_i and λ_i are real except that the parameter $\lambda_{10} = |\lambda_{10}|e^{i\alpha}$ could be complex potentially. There may exist terms like $H_2^\dagger H_3 S^n$ ($n \leq 2$) when choosing the $U(1)'$ charge $z_s = -6$ for $n = 1$ and $z_s = -3$ for $n = 2$. Without specifying the charge z_s , we may not discuss such terms in the rest of our paper. Considering the following vacuum structure which breaks the gauge symmetries to the electromagnetic symmetry $U(1)_Q$,

$$\langle H_i \rangle = \begin{pmatrix} 0 \\ \frac{v_i}{\sqrt{2}} e^{i\theta_i} \end{pmatrix}, \quad i = 1, 2, 3; \quad \langle S \rangle = v_s / \sqrt{2} \tag{7}$$

One can always use the global $U(1)$ symmetry to make $\theta_1 = 0$. In eq.(6), the only term that depends on the phase is $\lambda_{10} H_1^\dagger H_2 H_1^\dagger H_3$, when minimalizing the Higgs potential for the complex field component of the Higgs doublet H_1 , we are led to the following minimal condition

$$\sin(\alpha + \theta_2 + \theta_3) = 0, \quad \alpha = -(\theta_2 + \theta_3) \tag{8}$$

which indicates that α is tightly related to the vacuum phases, so CP symmetry is broken via the vacuum though it is not exactly spontaneous CP violation.

Spontaneously CP violation: When λ_{10} is real, namely, $\alpha = 0$ or π and $\theta_2 = -\theta_3$, there may exist some vacuum configurations that can cause spontaneous CP violation in such a three Higgs doublet model. As there is an Abelian gauge symmetry, the form of the Higgs potential is constrained. For a general discussion on those models, it is referred to [13]. When Yukawa interactions are not considered, it is possible to redefine the CP transformations of the Higgs fields, so that no spontaneous CP violation occurs in the Higgs sector. With Yukawa interactions of fermions, such redefinitions will induce complex Yukawa couplings.

Masses of gauge bosons: It is known that the gauge bosons will get their masses from their interactions with Higgs bosons after spontaneous symmetry breaking.

$$\mathcal{L}_H = \sum_{i=1}^3 (D^\mu H_i)^\dagger (D_\mu H_i) + (D^\mu S)^\dagger (D_\mu S)$$

the covariant differential operators can be easily written down and we omit them here. The mass term for the charged gauge bosons is simply given by

$$\frac{1}{4}g_2^2 [v_1^2 + v_2^2 + v_3^2] W_\mu^- W^{+\mu}.$$

For the neutral gauge bosons, their mass terms have the following forms

$$\begin{aligned} & \frac{v_1^2}{8}g^2 Z_0^\mu Z_{0\mu} + \frac{v_S^2}{8}g_1'^2 z_s'^2 B_\mu' B'^\mu \\ & + \frac{v_2^2}{8} \left(gZ_{0\mu} - g_1' z_2' B_\mu' \right) \left(gZ_0^\mu - g_1' z_2' B'^\mu \right) \\ & + \frac{v_3^2}{8} \left(gZ_{0\mu} - g_1' z_3' B_\mu' \right) \left(gZ_0^\mu - g_1' z_3' B'^\mu \right) \end{aligned}$$

with z_2' and z_3' the $U(1)'$ charges of the Higgs doublets H_2 and H_3 respectively, and $z_2' = -z_3' = -z_h'$ in our model. Where we have used the definition for the SM gauge bosons

$$\begin{aligned} Z_{0\mu} &= \frac{1}{\sqrt{g_1^2 + g_2^2}} [g_2 W_\mu^3 - g_1 B_\mu] = \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu, \\ A_\mu &= \frac{1}{\sqrt{g_1^2 + g_2^2}} [g_1 W_\mu^3 + g_2 B_\mu] = \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu. \end{aligned}$$

Here A_μ is the photon field and $g^2 = g_1^2 + g_2^2$. The mass matrix for $(Z_{0\mu}, B_\mu')$ is found to be

$$M^2 = \frac{1}{8} \begin{pmatrix} g^2 [\sum_{i=1}^3 v_i^2] & gg_1' z_h' [v_2^2 - v_3^2] \\ gg_1' z_h' [v_2^2 - v_3^2] & g_1'^2 [(v_2^2 + v_3^2) z_h'^2 + v_s^2 z_s'^2] \end{pmatrix}$$

Note that the off-diagonal terms can be made small when $v_2 \approx v_3$, so that there is a negligible mixing between $Z_\mu (Z_\mu = Z_{0\mu})$ and $Z_\mu' (Z_\mu' = B_\mu')$. Generally, it happens when imposing a permutation symmetry on the two Higgs doublets H_2 and H_3 under $H_2 \leftrightarrow H_3$, and in that case the off-diagonal terms vanish. While such a symmetry can not be an exact, otherwise the form of Yukawa terms will be highly constrained. In the spirit of simplicity for later phenomenological constraints, we will impose $v_2 \approx v_3$ and then experimental constraints from $Z - Z'$ mixing can be relaxed.

IV. PHENOMENOLOGICAL CONSTRAINTS OF Z' BOSON

We are now ready to consider in our model the phenomenological effects of Z' boson and focus mostly on the quark sector to constrain the parameters, $M_{Z'}$ and g'_1 . We shall show that the Z' boson in this model, generally, allow both flavor conserving and flavor changing couplings at the mass eigenstates of quarks. In the flavor conserving processes, we use the latest dijet search result to constrain the production rate of Z' and give some limits on $M_{Z'}$ and g'_1 . While in the flavor changing processes, we are going to investigate the t-channel Z' effects with only paying attention to the right-handed up quark part.

A. Discussion framework

The Lagrangian for $\bar{q}qZ'$ couplings is

$$\mathcal{L}_F = \sum_{i=1}^3 [\bar{Q}_L^i i\gamma^\mu D_\mu Q_L^i + \bar{u}_R^i i\gamma^\mu D_\mu u_R^i + \bar{d}_R^i i\gamma^\mu D_\mu d_R^i] \quad (9)$$

where the covariant differential operators on the left-handed and right-handed fermions are implicitly implied. We may rewrite interactions of gauge boson Z' in the gauge eigenstates as $g'_1 Z'_\mu J_{Z'}^\mu$,

$$J_{Z'}^\mu = \sum_{\psi} \sum_{i=1}^3 \bar{\psi}_i \gamma^\mu \left[\epsilon_i^{\psi_L} P_L + \epsilon_i^{\psi_R} P_R \right] \psi_i, \quad \psi = u, d$$

where the conventions are borrowed from [11]. After the gauge symmetries are broken down spontaneously, we need to diagonalize the mass matrices by redefining the quark fields,

$$\begin{aligned} u_R^i &= (V_{UR})_{ij} U_R^j, \quad u_L^i = (V_{UL})_{ij} U_L^j, \\ d_R^i &= (V_{DR})_{ij} D_R^j, \quad d_L^i = (V_{DL})_{ij} D_L^j. \end{aligned} \quad (10)$$

The CKM matrix is given by

$$V_{\text{CKM}} = V_{UL}^\dagger V_{DL}. \quad (11)$$

The transformation on the fermion fields Eq.(10) leads to

$$J_{Z'}^\mu = \sum_{\psi=(U,D)} \sum_{i,j=1}^3 \bar{\psi}_i \gamma^\mu \left[V_{\psi_L}^\dagger \epsilon^{\psi_L} V_{\psi_L} P_L + V_{\psi_R}^\dagger \epsilon^{\psi_R} V_{\psi_R} P_R \right] \psi_j.$$

The above interactions can give rise to FCNC effects when $V^\dagger \epsilon V \not\propto I$, which occurs when the Z' charges are not family universal, i.e., $\epsilon \not\propto I$. In our present consideration, the matrix ϵ is universal for the left and right handed fermions, and also for the up and down quarks in the first and second families,

$$\epsilon^{\psi_{L,R}} = \begin{pmatrix} +1 & & \\ & +1 & \\ & & -2 \end{pmatrix}.$$

Since only the combination $V_{\text{CKM}} = V_{UL}^\dagger V_{DL}$ is experimentally known, and the individual matrix $V_{\psi_{L,R}}$ are unknown, then the resulting $B^{\psi_{L,R}} \equiv V_{\psi_{L,R}}^\dagger \epsilon^{\psi_{L,R}} V_{\psi_{L,R}}$ is also unknown. One

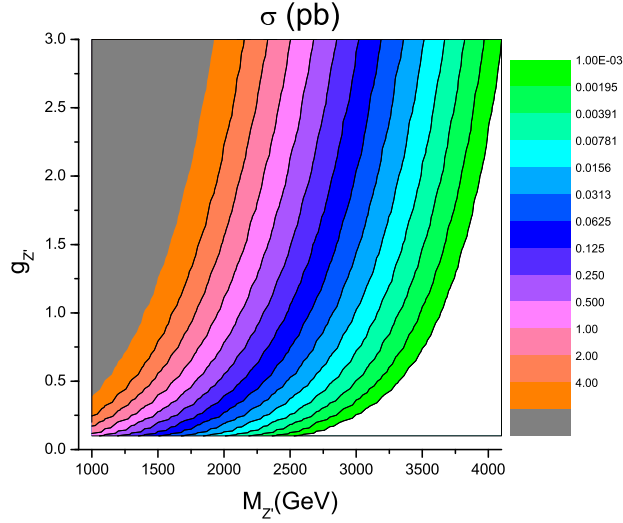


FIG. 1: Production rate or cross section ($pp \rightarrow Z'$) as contours of $M_{Z'}$ and gauge coupling $g_{Z'}$ at the LHC with $\sqrt{s} = 7$ TeV.

may make a rotation such that the coupling matrices have the following approximate form

$$B^{\psi_{L,R}} \simeq \begin{pmatrix} B_{11}^{\psi_{L,R}} & 0 & B_{13}^{\psi_{L,R}} \\ 0 & B_{22}^{\psi_{L,R}} & B_{23}^{\psi_{L,R}} \\ B_{13}^{\psi_{L,R}*} & B_{23}^{\psi_{L,R}*} & B_{33}^{\psi_{L,R}} \end{pmatrix}. \quad (12)$$

which fits to the phenomenology of light and heavy meson systems. More general discussions on the B meson physics with the above form of couplings have been given in [11]. For the down-quark sector, [11] demonstrates that such family non-universal $U(1)'$ scenarios can account for the currently observed discrepancies with the SM predictions for $B_s - \bar{B}_s$ mixing and the time-dependent CP asymmetries of the penguin-dominated $B_d \rightarrow (\pi, \phi, \eta', \rho, \omega, f_0) K_S$ decays. In the present paper, we shall discuss mainly on the up-quark sector and consider some effects on top quark observables.

We would like to point out that although $\epsilon^{\psi_L} = \epsilon^{\psi_R}$, it is not necessary to indicate that $B_{ij}^{\psi_L} = B_{ij}^{\psi_R}$ as V_{ψ_L} and V_{ψ_R} could generally be different. When $B_{ij}^{\psi_L} \neq B_{ij}^{\psi_R}$, there will be observable effect, such as forward-backward asymmetry. As the coupling matrices can have both diagonal and off-diagonal non-zero elements, there are also both flavor conserving and flavor changing phenomenology via Z' boson interactions.

B. Constraint from dijet search

In the subsection, we will focus on the flavor-conserving components and meanwhile treat the flavor-changing ones of $q_i \bar{q}_j Z'$ coupling matrix vanishing. We can then write the coupling matrix as, $G_{ij} \equiv V_{\psi_L}^\dagger \epsilon^{\psi_L} V_{\psi_L} P_L + V_{\psi_R}^\dagger \epsilon^{\psi_R} V_{\psi_R} P_R = \epsilon \delta_{ij}$. Coupling of this form can be achieved by properly adjusting V_{ψ_L} and V_{ψ_R} .

We mainly focus on the TeV scale Z' in this sector. In Fig.1, we plot a color map of the cross section($pp \rightarrow Z'$) at the LHC with $\sqrt{s} = 7$ TeV as functions of $M_{Z'}$ and gauge coupling $g_{Z'}$. At the LHC, Z' is produced through the channel $q\bar{q} \rightarrow Z'$ and then decay to

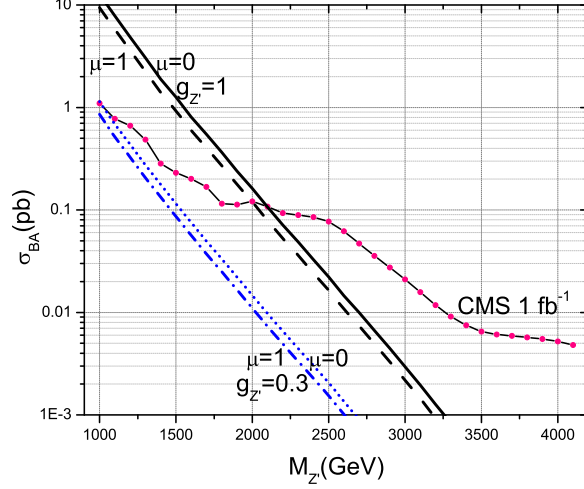


FIG. 2: Constraints from dijet search at the CMS(1.0 fb^{-1}) [14]. Black solid(dashed) line denotes the $\mu = 0(\mu = 1)$ with $g_{Z'} = 1$, and blue dot(dot-dashed) line represents the $\mu = 0(\mu = 1)$ with $g_{Z'} = 0.2$. Red-point line indicates the 95% CL upper limit on $\sigma \times B \times A$. See text for details.

quark pairs and/or lepton pairs, depending on μ , the ratio of quarks and lepton's charge. Search for s-channel resonance can put lower bound on the mass $M_{Z'}$ and correspondingly upper bound on gauge couplings $g_{Z'}$.

The dijet searches [14, 15] are directly connected with s-resonance Z' . It can constrain this $U(1)'$ model as shown in Fig.2. We use the result from CMS Collaboration [14]. The result can be easily compared with the total cross section(σ) at parton level and effective cross section(σ_{BA}). Here σ_{BA} stands for $\sigma \times B \times A$, where B for branching fraction to dijet and A for acceptance. The value of $A \sim 0.6$, the same one used in CMS Collaboration [14], is independent of the mass of Z' . The branching ratio B is different for $\mu = 1$ and $\mu = 0$ (leptophobic model). For $M_{Z'}$ of TeV scale, quarks and leptons' masses can be neglected and straightforward calculation gives $B = 1/4$ for $\mu = 1$ and $B = 1/3$ for $\mu = 0$. Correspondingly, the upper limits are different in two cases (for $\mu = 1$, constraint from dilepton search need to be considered, as discussed below). As we can see from the Fig.(2), the exclusion limit for $M_{Z'}$ is slight changed, up to $\mathcal{O}(100)$ GeV. As the constraints depends on the gauge couplings $g_{Z'}$, we plot for two values of $g_{Z'}$. For $g_{Z'} = 1$, the figure shows that $M_{Z'} < 2.1$ TeV is excluded at 95% confidence level(CL), while for $g_{Z'} = 0.3$ the limit is lowered to 1.0 TeV.

C. Constraint from dilepton search

For $\mu = 0$, there is no constraint from leptonic processes since no interaction exists between Z' and leptons. In principle, for $\mu \neq 0$, in addition to the constraint from dijet search, we also need combine with the limit from dilepton search [16, 17], $Z' \rightarrow l^- l^+$ ($l = e, \mu$). Since there are only exclusion figures but no accessible and quantitative numbers, we can not repeat the same process as dijet case, but only give some qualitative analysis by comparing with sequential standard model(SSM).

For standard-model-like Z'_{SSM} , with $g_V^u = 0.29, g_A^u = 0.50, g_V^d = -0.33, g_A^d = 0.52$ and

$\text{Br}(Z'_{\text{SSM}} \rightarrow l^- l^+) = 6.73\%$, CMS experiment [16] has excluded at 95% confidence level the mass of Z'_{SSM} , $M_{Z'} > 1940$ GeV. For our model, several differences can modify the limit. The branching ratio of $Z' \rightarrow l^+ l^-$, $\text{Br}(Z' \rightarrow l^- l^+)$ is quadratically dependent on the μ with $B_{l^- l^+} \propto \mu^2 \times \frac{1}{4} \times \frac{1}{6}$. The factor $\mu^2/4$ arises because other 3/4 of Z' decay to quarks for $\mu = 1$ and the factor $\frac{1}{6}$ originates the fact that, of the leptonic decaying Z' , half of them decay to neutrinos and $\frac{1}{3}$ to τ s. So the ratio of production rate reads

$$R_\sigma = \frac{\sigma(pp \rightarrow Z' \rightarrow l^+ l^-)}{\sigma(pp \rightarrow Z'_{\text{SSM}} \rightarrow l^+ l^-)} \simeq \frac{4g_{Z'}^2}{g_V^2 + g_A^2 + g_V^2 + g_A^2} \times \frac{\mu^2/24}{0.0673}. \quad (13)$$

We can use the above quantity to estimate the bounds for $M_{Z'}$ for different $g_{Z'}$. For $\mu = 1$ and $g_{Z'} = 0.3$, $R_\sigma \simeq \frac{5}{16}$, and this will change the exclusion limit of $M_{Z'}$ to 1.6 TeV by comparing the figure presented in [16]. For $\mu = 1/2$ and $g_{Z'} = 0.3$, the limit can be shifted to 1.25 TeV. In both case, limits from dilepton search are more stringent than those from dijet search as expected, since leptonic final states have better discriminating power.

D. The t-channel Z' effects

As mentioned above, this model also allows flavor-changing and left-right asymmetry couplings. In such a case, the limits from s-channel dijet or dilepton searches can not be literally applied. The trends show that the constraints on the $M_{Z'}$ and $g_{Z'}$ are correlated, the smaller $g_{Z'}$, the more loosely constrained $M_{Z'}$. We also know that B physics can give stringent constraint on the coupling of down quark sector. So in the section, we shall only consider some effects on top quark sector within the lower $M_{Z'}$ region.

Both CDF and D0 have observed forward-backward asymmetry of top pair production at the Tevatron [18–23]. The CDF experiment has reported the forward-backward asymmetry at the parton-level [21, 22] (We mostly compare with the CDF result since it is at parton level which can be directly compared with theoretical calculation.),

$$A^{t\bar{t}} = 0.158 \pm 0.072 \pm 0.017.$$

In the SM with NLO-QCD corrections, result is given by

$$A_{SM}^{t\bar{t}} = 0.058 \pm 0.009.$$

Even within the electroweak correction [24], standard model still can not give such a large asymmetry. The CDF experiment has also measured the total cross section $\sigma_{t\bar{t}} = 7.50 \pm 0.48$ pb [25] for top quark mass $m_t = 172.5$ GeV, which is in agreement with the theoretical prediction in the SM $\sigma_{t\bar{t}} = 7.46_{-0.80}^{+0.66}$ pb [26–29]. The agreement of the cross section motivates light flavor changing Z' effects. There are many related works on discussing this effect [30–38]. In the following, we shall give a short discuss in our present model.

In our model, when the coupling between u and t quark, $g_{ut}^{L,R}$ are not vanishing and $g_{ut}^R \neq g_{ut}^L$, it can lead to forward-backward asymmetry of top pair production and same top production at hadron collider. In this subsection, we analyse in our model such effects and in addition constrain the parameters. Our conclusion is that such a model can not account for all the forward-backward asymmetry observed at Tevatron if satisfying the limit from the same top production at the LHC [39].

For simplicity, we may only consider the typical case $B_{13}^{UL} = 0$ and give an upper bound on $g_{uR} \equiv g_{ut}^R$. In Fig. 3, we show the colored map of A_{FB} in the possible range of parameters:

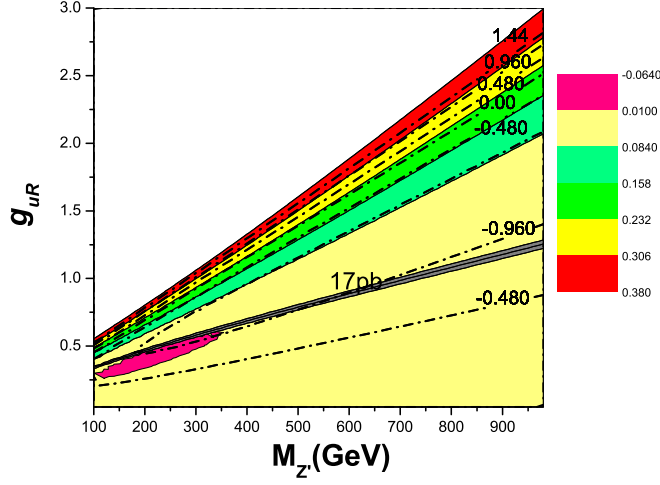


FIG. 3: Colored map for forward-backward asymmetry as function of g_{uR} and $M_{Z'}(\text{GeV})$. The dot-dashed lines are contours for the total cross section from NP. The dark-grey band indicates the limit on the cross section of same top production at the LHC. We allow 10% variance to make the band easy to see. Region above the band gives cross section larger than 17pb.

$100 \text{ GeV} < M_{Z'} < 1000 \text{ GeV}$ and $0.05 < g_{uR} < 3$. Such t-channel process will also contribute to the total cross section of $t\bar{t}$ pair production denoted by σ_{NP} (here NP labels New Physics), we plot the contours of σ_{NP} in dot-dashed lines in the same figure.

When the t-channel Z' boson exchange is responsible for the asymmetry, it will also induce two top quarks or two anti-top quarks production. The experiments at Tevatron have already constrained the cross section, while the experiment at LHC [39] can give even more stringent constraint on the coupling for the same sign top quark production ($uu \rightarrow t\bar{t}$) through the t-channel or u-channel. In Fig. 3, we indicate, in the $M_{Z'} - g_{uR}$ plot, with a grey band of 17 pb cross section for the $uu \rightarrow t\bar{t}$ production reported by the LHC experiment. We allow 10% uncertainty in order to make the band easily seen. The region above the grey band is disfavored, while the region below the band is allowed and the resulting A_{FB} presents a reasonable prediction in our model.

V. CONCLUSIONS

We have presented a simple UV complete and family non-universal $U(1)'$ gauge model in which the anomaly is canceled by appropriately choosing the $U(1)'$ charges of the SM particles without introducing extra fermions. As the anomaly is canceled separately in the lepton and quark sectors, which may leave a room to escape the strong constraints from the direct searches for the final states with two leptons. Also the $U(1)'$ charges of the first and second families are taken to be the same in order to suppress the FCNC effects. To build a realistic model via spontaneous symmetry breaking, it requires one Higgs doublet with zero $U(1)'$ charge and two Higgs doublets and a singlet scalar with non-zero $U(1)'$ charges. As the $U(1)'$ charges of the first and second families are different from those of third family, there exist in general both flavor conserving and flavor changing couplings of the Z' boson after spontaneous symmetry breaking and rotating to the mass eigenstates of quarks and

leptons.

In flavor-conserving case, we have used the latest dijet and dilepton search to constrain the mass of Z' and gauge coupling $g_{Z'}$. For a typical $g_{Z'} = 0.3$, at 95% confidence level, $M_{Z'}$ is large than 1.0 TeV, and 2.1 TeV for $g_{Z'} = 1$. The constraints depend on whether such Z' couples to leptons. The limits can be shifted to higher value, depending on the ratio of $U(1)'$ charges between quark and lepton sector, μ . When $\mu = 0$, this model has a leptophobic structure and lepton sector impose no constraint.

For flavor-change couplings, the Z' boson can in general couple with left-handed and right-handed quarks and leptons differently, so it can contribute to the forward-backward asymmetry(FBA) of the top quark pair production at the Tevatron. Such t-channel process with flavor changing Z' boson exchange, in addition to the constraint from the CMS experiment on the cross section of the same top production, indicate that such a Z' can not solely account for the FBA observed.

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